Attitude Visualization of the Cassini Spacecraft Using Dview

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ABSTRACT

The Cassini spacecraft has been designed so that it may point in virtually any direction provided that certain attitude constraints (to protect sensitive instruments and sensors from exposure to bright bodies such as the Sun) are not violated. However, during the seven year trip to Saturn and the four year tour of the Saturnian system, the Cassini spacecraft will be exposed to varying mission geometries including Low Earth Orbit (LEO), planetary flybys, deep space, Saturn orbit, and Titan flybys. Such widely varying conditions and constraints present a formidable challenge to engineers responsible for safely pointing the spacecraft and for achieving science objectives. A behavioral pointing model was implemented in the Cassini flight software to facilitate pointing commands and an onboard Constraint Monitor helps prevent dangerous spacecraft pointing. Nevertheless, ground operators are still ultimately responsible for achieving science objectives and for ensuring spacecraft safety. To this end, Dview, a general-purpose 3-dimensional modeling and animation system developed at the Jet Propulsion Laboratory, was modified to assist attitude control engineers in creating constraint-free pointing command sequences and analyzing telemetered attitude data. Thus far Dview's primary use at JPL has been visualization of articulated spacecraft and their interplanetary trajectories. Recent enhancements to Dview have enabled visualization of the spacecraft-centered celestial sphere and projection of instrument fields-of-view, extended bodies, and constraint regions onto the celestial sphere.

INTRODUCTION

The Cassini Mission includes a seven year cruise phase to Saturn and four year tour of the Saturnian system. The Cassini spacecraft, which comprises the orbiter and Huygens Probe, will launch in October 1997 and will receive gravity assists from Venus (twice), Earth, and Jupiter during its long journey to Saturn, where it will arrive in June 2004. While in orbit around Saturn, the spacecraft will release the Huygens Probe into the atmosphere of Titan and will perform numerous scientific observations of Saturn, Titan, the rings, and Saturn's many satellites.

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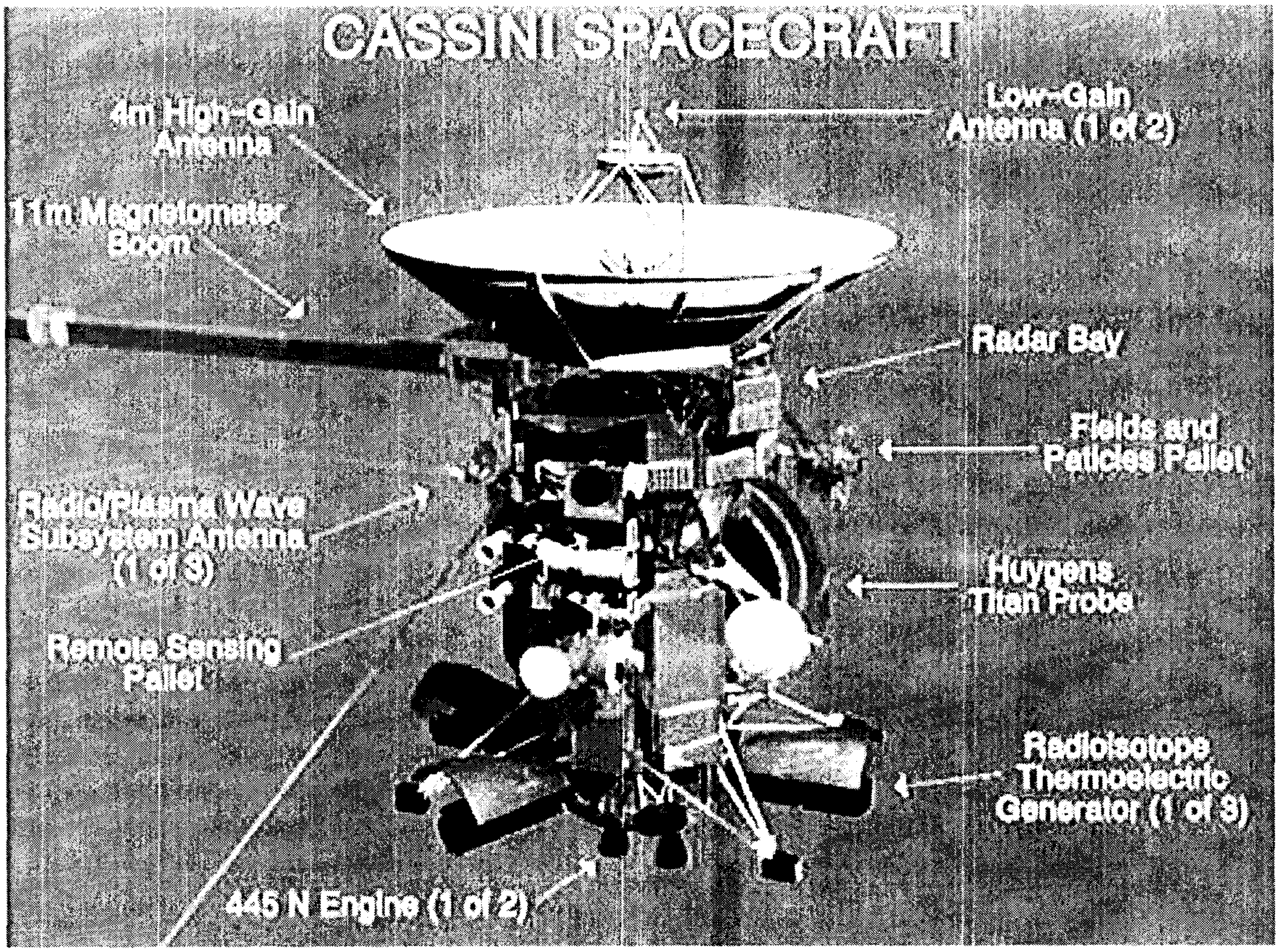

Figure 1: The Cassini Spacecraft

Pointing Cassini

Pointing the Cassini spacecraft has been simplified through a behavioral model which allows operators to specify a target at which a body-fixed vector should point [1]. This pair of vectors—known as the primary target and primary body vector—specifics two components of the attitude. The third component—the angle about the primary pair—is specified by a pair of vectors known as the secondary target and secondary body vector. Given a primary and secondary pair of vectors, the flight software will point the primary body vector directly at the primary target and will minimize the angle between the secondary body vector and the secondary target, provided that neither the target vectors nor the body vectors are (nearly) collinear. For example, an operator could specify that the high gain antenna (HGA) should point directly at the Sun and that low gain antenna 2 (LGA2) should point as close as possible to the Earth. The spacecraft, given coefficients which specify the vectors from the sun to the earth and from the sun to the spacecraft over time, would then compute the associated attitude which achieves the commanded objectives.

The behavioral pointing model relieves spacecraft operators from the drudgery of computing the spacecraft attitude on the ground and uplinking it

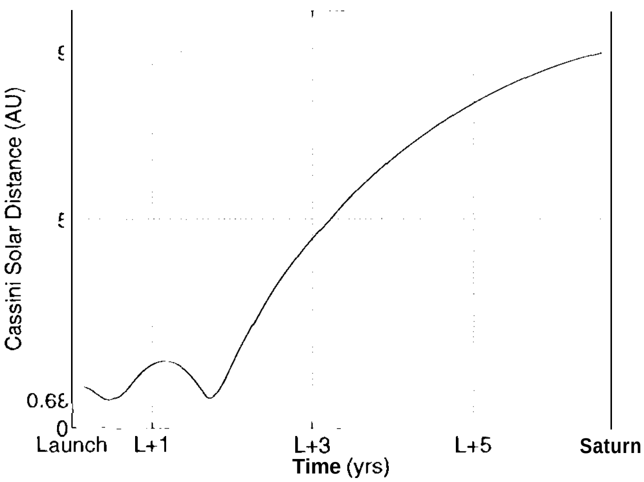

Figure 2: Cassini Solar Distance (October 6,1997 launch)

to the spacecraft as a quaternion or some other attitude parametrization. Furthermore, target motion compensation is implicitly handled because targets are represented by time-dependent vectors and the spacecraft attitude is recomputed at regular intervals.

Another part of the Cassini flight software—the Constraint Monitor-was designed to protect the spacecraft from pointing problems or mistakes which could endanger it or jeopardize the mission. The Constraint Monitor contains a set of rules such as "keep the stellar reference unit (SRU) boresight at least 30° from the Sun." If the Constraint Monitor anticipates or detects a violation of any of its active rules, it attempts to prevent or correct the problem. A more detailed description of the Cassini Constraint Monitor can be found in [1]. Following are two examples of constraints levied on Cassini.

<u>Constraint Example: Thermal/Sun Pointing</u>

As shown in fig. 2, the Cassini trajectory to Saturn brings the spacecraft within 0.68 AU of the Sun at its closest approach and as far as 9 AU at Saturn. This wide range in solar distances results in a greatly varying thermal environment; the spacecraft is hot in the early part of the mission and cold during the tour. The thermal problem has, in part, been alleviated by shade from the large high-gain antenna (HGA) which will be pointed toward the Sun during the early part of the mission. Off-sun pointing, which is necessary during trajectory correction maneuvers, sensor and instrument calibrations, and high-data-rate communications is limited by a thermal constraint which dictates total allowable off-sun time as a function of solar distance.

<u>Constraint Example: Extended Bodies in the Stellar Reference Unit Field-of-View</u>

Star data collected from the Stellar Reference Unit (SRU), a CCD camera, is used for attitude determination. An extended body (i.e., a body whose angular radius as seen from Cassini is greater than 0.25°) may obstruct all or part of the CCD field-of-view, reducing--or possibly eliminating--star updates to the onboard attitude estimator. Therefore, *all extended bodies must be kept at least 30° from the SRU boresight.* This particular constraint is simple to accommodate in deep space where the angular radius of each planet is small; however, it may be difficult to accommodate during planetary flybys and the tour.

The Spacecraft-Centered Celestial Sphere

The spacecraft-centered celestial sphere is a powerful tool for visualizing spacecraft attitude [2, 3]. This directions-only geometry places the spacecraft at the center of a sphere and projects the world as seen from the spacecraft onto the sphere, removing distance from the problem. In this approach, spacecraft body vectors are represented as points on the unit sphere, cones (angles about a spacecraft body vector) are represented as small circles, and lines are projected onto the sphere as great circle arcs. Celestial objects such as stars (represented as points) and planets (represented as small circles with radius equal to the angular radius of the planet) can also be projected onto the sphere. The spacecraft-centered celestial sphere can be fixed to either the spacecraft body or an "inertial" coordinate system such as J2000 or Earth-Centered Inertial (or any other coordinate system, for that matter).

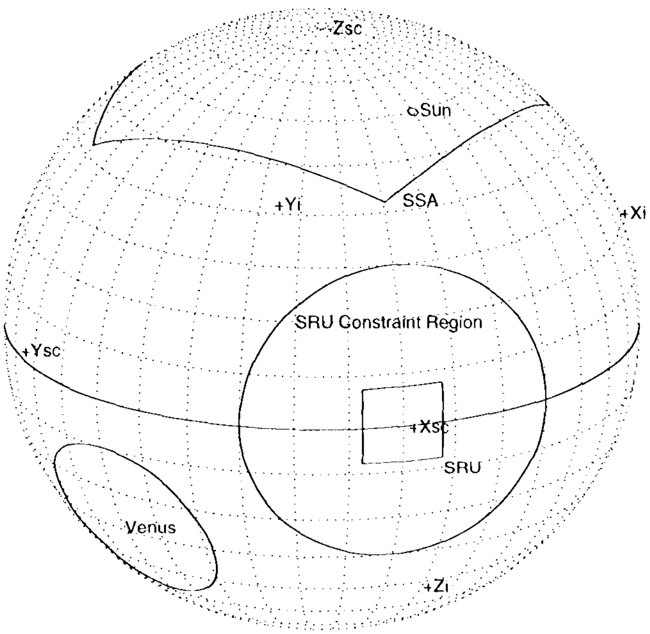

Figure 3: Spacecraft-Centered Celestial Sphere Example

Figure 3 provides a simplified example of the spacecraft-centered celestial sphere for Cassini. In this example, the field of view of the Sun Sensor Assembly (SSA) is represented by the "warped" square surrounding the spacecraft -Z axis (-Z,C), towards the top of the sphere. The Stellar Reference Unit (SRU) is represented by the small square along the spacecraft +X axis ($+X_{sc}$). Venus is represented by the small circle with angular radius 19°, and the Sun can be seen in the SSA field of view. We have also included the axes of a representative inertial coordinate system ($+X_i$, $+Y_i$, and $+Z_i$).

This simplified example does not include many desirable features such as stars and constraint regions, but it serves to illustrate the utility of the celestial sphere. For example, it is readily apparent that the scenario depicted in fig. 3 does not violate the extended body constraint described earlier because no extended bodies intersect the SRU field of view (FOV). However, it is also clear that the angle between the Sun and the spacecraft $-Z_{sc}$ axis (also the HGA boresight) is about 30°, which would violate the thermal constraint.

DVIEW

Dview is a trajectory visualization tool developed at the Jet Propulsion Laboratory. Dview is written in C, C++, and X/Motif, and supports OpenGL or Mesa. It runs on Silicon Graphics, Hewlett-Packard, Sun/Solaris, and Linux platforms. Interestingly, it evolved from a doctoral dissertation on rider control of equine locomotion [4]. Nonetheless, at JPL it's been used exclusively for spacecraft visualization. In conjunction with DARTS, a real-time dynamics simulator which was also the recipient of NASA's Software of the Year Award in 1997, Dview can be used to dynamically (see `http://dshell.jpl.nasa.gov`). Dview is also used by the Mars Global Surveyor project to show, in real-time, the current spacecraft attitude and solar panel orientation (see `http://marsweb.jpl.nasa.gov`).

Dview provides a graphical user interface to create articulated spacecraft models as well as an animation language for commanding those models in real time and accessing relevant ephemeris information.

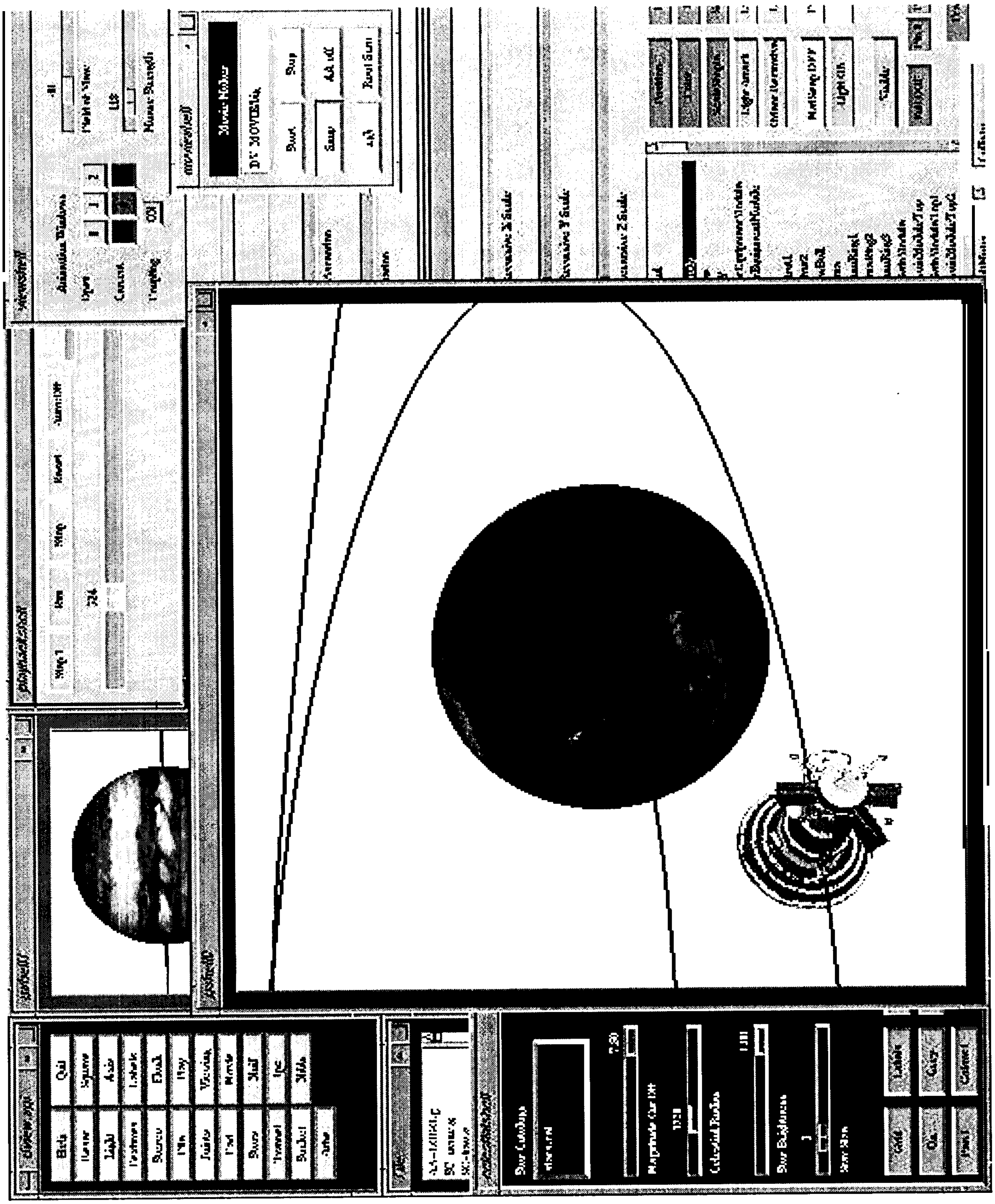

Figure 4: The Dview Graphical User Interface

A screen shot of Dview is provided in fig. *4*, showing controls for spacecraft model construction, animation control, and lighting, among others, as well as two views of the same scenario.

Full-color, 3-dimensional models can be interactively constructed from a rich set of primitives. Typically, spacecraft models created with Dview are constructed using a few hundred primitives. The objective is to construct models that appear realistic and represent the main components and moving parts on the spacecraft. Details which would ordinarily be included in a full CAD model are not of concern whereas articulated solar panels, cameras, instruments, probes, mirrors, reaction wheels and primary components usually are included in Dview models. Figure 5 shows a close-up of Cassini just after probe release; the major structural and hardware components of Cassini are clearly included, but extreme detail has been intentionally excluded.

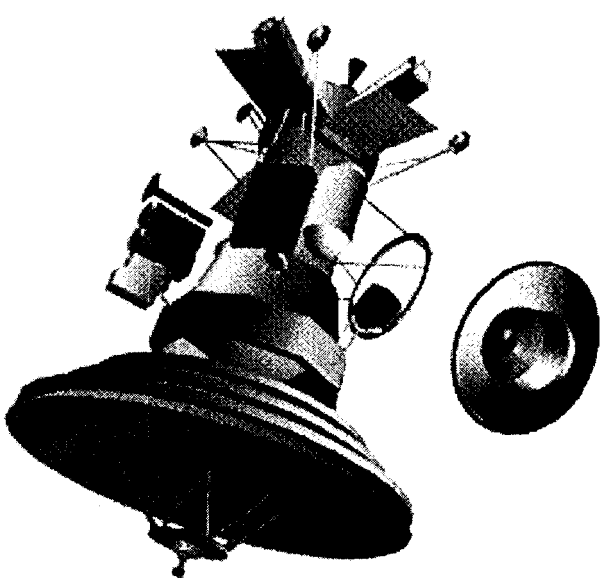

Figure 5: Dview-Generated image of Huygens Probe Release

Dview stores models internally in a kinematic tree which simplifies the definition of articulated parts. For example, specification of a pin, or arbitrary rotation axis, is used to define an articulated component such as a solar panel. The pin provides the axis about which the part (and children) rotates. Orientation of the part about its pin axis such (e.g., the deployment of a solar panel) is easily updated in real-time via a rotation command, which specifies the desired angle of rotation about the pin.

Dview's real-time animation language provides the commands which are used to control the position and attitude of the objects in the scene as well as the current rotation angle for any hinged parts. All of the commands are simple text strings consisting of a keyword and arguments. For example, the following commands set the spacecraft attitude, move a reaction wheel, and fire two thrusters:

```
# Set the spacecraft attitude quaternion
Q basebody 0 0 0 1
# Rotate reaction wheel by 30 degrees
M ReactionWheel 30.0
# Turn 2 thrusters on simultaneously
ON thrust1/ON thrust2
```

The Dview language has grown to several hundred commands which allow the user to build trajectories, turn objects on and off, set data scale factors, track, attach or lookout from parts, and maintain pointing orientation, among other features (a book on Dview is in development). Commands can be sent to Dview using UNIX sockets, NDDS, JPL's Tramel, or they can be stored in a file which is read in and played back at the desired frame rate.

The TCL command language can be utilized to embed Dview commands into programming constructs such as loops and mathematical expressions. Additionally, animations can be stored to file for creating Quicktime and MPEG

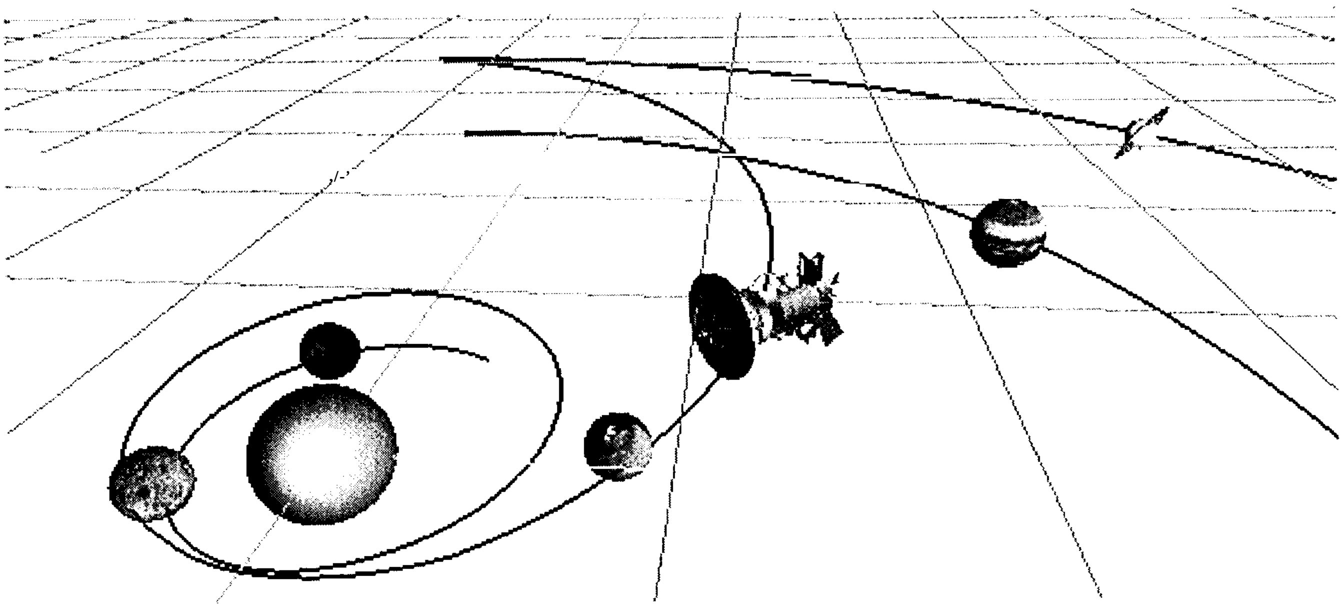

Figure 6: Cassini Trajectory Displayed in Dview

movies. In progress work includes converting the user interface from X/Motif to lava and allowing the export of Dview model files to VRML.

Multiple Views

Figure 6 shows the interplanetary cruise path of Cassini; here Cassini is in a sun-pointed orientation prior to the Jupiter flyby. In this figure we have included the trajectory of the spacecraft as well as the trajectories of Jupiter and Saturn. In addition, a grid representing the ecliptic plane provides a three-dimensional quality to the image. The size of the figures representing the sun, the planets, and the spacecraft are exaggerated for illustrative purposes. This type of figure is particularly useful for illustrating trajectories, but users often find it difficult to accurately visualize the spacecraft attitude. One of Dview's strengths is its capability to change the location of the observer as well as how trajectories and the "world" are viewed. Dview allows users to quickly switch to the spacecraft-centered celestial sphere, which, as described earlier, is a powerful tool for attitude visualization.

Figure 7 shows the Cassini-centered celestial sphere during the Venus flyby in April 1998. This image shows the fields of view of the sun sensor assembly (SSA) and stellar reference unit (SRU), constraint regions, all stars down to visual magnitude four, and the directions to the center of the planets and the Sun (represented by the small texture-mapped images). The disk of Venus is represent by the small circle centered at Venus (on the left side of the sphere); Dview automatically computes the angular radius of the small circle based on the distance from the spacecraft to the planet. In this example the SRU, represented by the small square and inscribed circle near the center of the image, and the SSA, represented by the large square on the right, appear to have unobstructed views of the sky, as required. However, fig. 7 also shows that the field of view of the SRU is threatened by Venus as the angular radius of Venus grows.

Conclusion

Dview, a powerful trajectory visualization tool developed at the Jet Propulsion Laboratory, has been modified to allow users to view the

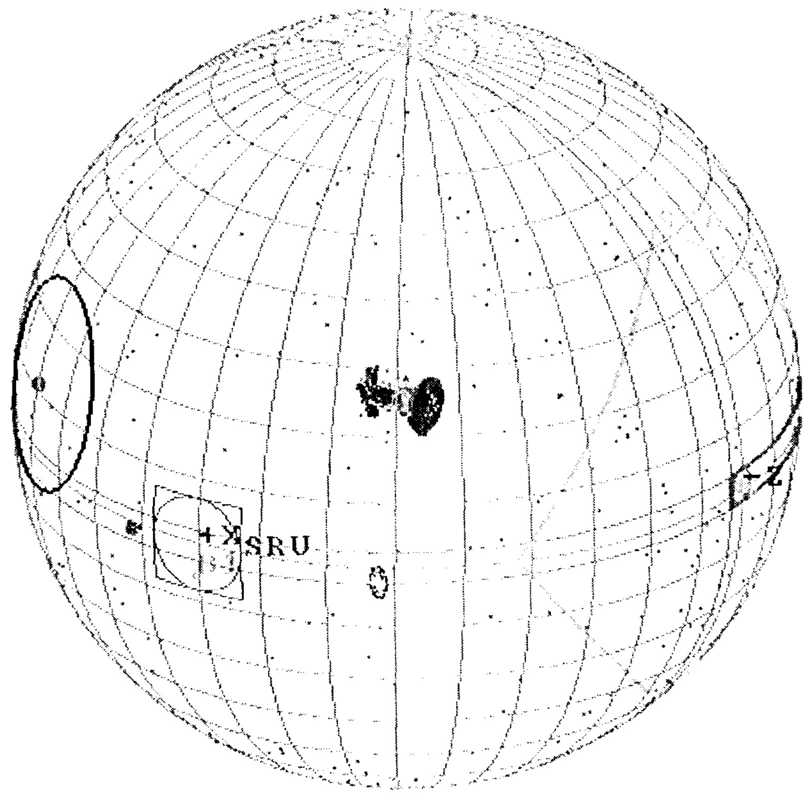

Figure 7: Spacecraft-Centered Celestial Sphere Image of Cassini Generated by Dview.

spacecraft-centered celestial sphere and to project on to the sphere information such as constraint regions, fields of view, planets, and stars. Dview will be used by attitude control engineers on the Cassini project to design command sequences and to resolve anomalies.

Additional Information

Additional information about Dview can be found at `http://dview.jpl.nasa.gov`.

References

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[2] Wertz, J. R., (Ed.), *Spacecraft Attitude Determination and Control*, Dordrecht: D. Reidel Publishing Company, 1984.

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